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DEVELOPMENT OF SUSTAINABLE, INNOVATIVE AND ENERGY-EFFICIENT CONCRETE, BASED ON THE INTEGRATION OF ALL-WASTE MATERIALS: SUS-CON PANELS FOR BUILDING APPLICATIONS

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ABSTRACT:

The building sector requires the worldwide production of 4 billion tonnes of cement annually, consuming more than 40% of global energy and accounting for about 8% of the total CO₂ emissions. The SUS-CON project aimed at integrating waste materials in the production cycle of concrete, for both ready-mixed and pre-cast applications, resulting in an innovative light-weight, ecocompatible and cost-effective construction material, made by all-waste materials and characterized by enhanced thermal insulation performance and low embodied energy and CO₂. Alkali activated “cementless” binders, which have recently emerged as eco-friendly construction materials, were used in conjunction with lightweight recycled aggregates to produce sustainable concrete for a range of applications. This paper presents some results from the development of a concrete made with a geopolymeric binder (alkali activated fly ash) and aggregate from recycled mixed plastic. Mix optimisation was achieved through an extensive investigation on production parameters for binder and aggregate. The mix recipe was developed for achieving the required fresh and hardened properties. The optimised mix gave compressive strength of about 7 MPa, flexural strength of about 1.3 MPa and a thermal conductivity of 0.34 W/mK. Fresh and hardened properties were deemed suitable for the industrial production of precast products. Precast panels were designed and produced for the construction of demonstration buildings. Mock-ups of about 2.5 x 2.5 x 2.5 m were built at a demo park in Spain both with SUS-CON and Portland cement concrete, monitoring internal and external temperatures. Field results indicate that the SUS-CON mock-ups have better insulation. During the warmest period of the day, the measured temperature in the SUS-CON mock-ups was lower.

Keywords: Sustainable concrete, recycled aggregate, geopolymeric binder, precast concrete, mock-up monitoring.

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INTRODUCTION

According to data from United Nations Environmental Programme (UNEP) reported in [1], building and construction sector employs about 111 million people around the world, consuming 20% of water and between 25% and 40% of energy, while producing between 30% and 40% of solid waste and 30 and 40% of global greenhouse gases (GHGs).

Interventions in the field of sustainable, alternative building materials are essential for achieving the international targets set for stopping the global warming and for a sustainable development. For this reason, European Commission defined an ambitious agenda where the development of innovative, green building materials is a priority. In this context, the 7th Framework Programme (FP7) launched the call EeB.NMP.2011-1 “Materials for new energy efficient building components with reduced embodied energy”.

The SUS-CON (SUStainable, innovative and energy-efficient CONcrete, based on the integration of all-waste materials) project, funded under that call, aimed at developing new concepts and technology routes to integrate secondary materials in the production of concrete, for both ready-mixed and pre-cast applications, resulting in an innovative, eco-compatible and cost-effective construction material, characterised by:

- light-weight;
- low embodied energy;
- low CO₂ footprint;
- improved thermal and acoustic insulation performance (multi-functionality).

The focus of the project was on waste materials largely available across Europe that are not currently recycled, investigating aggregate and binder from secondary materials and in turn developing a 100% recycled concrete. Whereas aggregates were obtained from lightweight materials (such as waste tyres, MPW, WEEE and rigid polyurethane foams), binders were developed from aluminosilicate-rich precursors (such as coal ash, metallurgical slag, perlite tailings) and alkali materials as activators.

Some details on the project activities can be found in published literature [2, 3] and on the project website [4]. The project was successfully completed in 2015, with the industrial production of panels, blocks and ready-mix floor screed with selected recipes of SUS-CON materials. Three demonstration sites have been set up in Europe (Spain, Turkey and Romania) with SUS-CON and Portland cement concrete reference buildings.

In this paper, some results from the development of a concrete made with a geopolymeric binder (alkali activated fly ash) and aggregate from recycled mixed plastic for the production of precast panels are presented. The mix recipe was developed for achieving the required fresh and hardened properties. Precast panels were designed and produced for the construction of the demonstration buildings. Mock-ups of about 2.5 x 2.5 x 2.5 m were built at a demo park in Spain both with SUS-CON and Portland cement concrete, monitoring internal and external temperatures.

MATERIALS AND METHODS

Recycled aggregate development

Mixed Plastic Wastes (MPW), resulting from the sorting process of plastic recycling, were explored in this study to assess the viability to process them into lightweight concrete aggregates. A technological process to produce innovative lightweight aggregates was developed in collaboration with an Italian company working in material recycling sector (Centro Riciclo Vedelago). Plastic scraps, used as raw material, mainly consist of polyethylene (PE) and polypropylene (PP), but also include residuals of polyethylene terephthalate (PET) and minimal other impurities. The production process basically consists of an extrusion and an expansion stages, resulting in two different aggregate types. The process parameters have been accurately optimized taking also into consideration product quality and production costs. Lightweight aggregates, hereafter referred as Remix (RX), with different density were produced (RX HD – densified flakes with higher density – and RX LD – expanded granules with lower density), see Figure 1. RX HD aggregates are produced by processing the raw material into an extruder, where plastic is melted and densified, then it is cooled and reduced in suitable sizes. RX LD aggregates are obtained by a patented foaming process, using foaming agents also from waste, applied on densified flakes (European Patent EP1598164A1).

In order to assess the suitability of the produced aggregates for concrete manufacturing, these have been fully characterized in terms of physical, mechanical and chemical properties according to specific standards, as reported in Table 1. Remix aggregates, both densified and expanded type, have shown particle density lower than 2000 kg/m^3 , therefore they can be classified as lightweight aggregates according to EN 206-1 [5]. Moreover, results of chemical tests confirmed their compliance with the standards' requirements and according to HSE (Health, Safety and Environment) assessments the developed aggregates can be classified as non-hazardous.

Table 1 Overview of mixed plastic (Remix - RX) aggregates properties according to specific standards.

RX AGGREGATES PROPERTIES*									
Aggregate typology	Geometrical	Physical			Mechanical	Chemical			
	EN 933-1	EN 1097-3	EN 1097-6		EN 13055-1	EN 1744-1			
	Particle size [mm]	Loose bulk density [kg/m^3]	Particle density [kg/m^3]	Water absorption [%]	Compressive strength [N/mm^2]	Sulphates (%)	Chloride salts (%)	Sulphur (%)	Organic impurities
RX HD (densified)	0-2	-	-	-	-	-	-	-	-
	3-7	290	810	10	250	0.01	0.13	0.03	-
RX LD (expanded)	8-12.5	359	660	22	215	0.15	0.02	1.06	absent

* The standards applied are not specific for the tested materials (recycled mixed plastic). This led to some variability in the results. Moreover, some standards should be applied for size lower than 4 mm, so not all the aggregates sizes were tested.



Figure 1 Mixed plastic scraps (a) used as raw materials for RX aggregates production: densified flakes (b) and expanded granules (c).

Alkali activated binder

Fly ash (pfa) was supplied by Power Minerals Ltd., Drax Power Station, North Yorkshire, UK. The average dimension (d_{50}) of the powder particle was 18 μm . The mineralogical composition was assessed through X-ray diffraction (XRD) with the following setting: pure copper-K-Alpha 1 radiation with wavelength 1.54 \AA , X-ray generator @ 40 kV and 40 mA, angular range 5° to 70° (2θ) with a step close to 0.017° . The Rietveld method, adding and blending 20% in weight of corundum (Al_2O_3) as internal standard, allowed a quantitative estimation of the amorphous and crystalline fractions. The amorphous content was found to be 86%, whereas quartz (4.6%), mullite (8.1%), hematite (0.5%) and magnetite (0.8%) were the main crystalline phases detected.

Commercial chemicals were used for the activation: solid NaOH of commercial grade (99% purity) and sodium silicate solution with $\text{SiO}_2:\text{Na}_2\text{O}$ mass ratio = 2. Mass composition of the commercial sodium silicate solution, provided by Woellner GmbH & Co KG, Ludwigshafen, Germany, with trade name “Betol 52”, was Na_2O = 15%, SiO_2 = 30%, H_2O = 55%, in weight. NaOH solution was prepared by dissolving solid NaOH in tap water (300 g of NaOH dissolved in 700g of tap water).

The proportions of these two alkalis and their concentrations were defined as follows:

- Alkali dosage (M^+): mass ratio of total sodium oxide (Na_2O) in the activating solution of pfa;
- Alkali modulus (AM): mass ratio of sodium oxide to silica in the activating solution.

A previous study on the effect of chemical dosage on the reaction development in a pfa-based system [6] indicated that the mechanical strength of mortar increases with the increase of the AM until an optimum value that was found to be in the range 0.95 – 1.25. Subsequently, it decreases until a residual value, due presumably to the reduced amount of available silica. The effect of the M^+ increase was also associated with an increase in the compressive strength of mortars, with a maximum of about 60 MPa for values in the range 11 – 12%, but the incremental gain narrowed when M^+ was higher than 9.5%. Moreover, higher dosages were found to trigger fast setting behaviour, besides implying high production costs and higher environmental burden. As a compromise between these conflicting trends, alkali dosages were fixed at $M^+ = 7.5\%$ and $AM = 1.25$, ensuring a compressive strength (measured on mortar) of about 25 – 30 MPa. Some details can also be found in [7].

The water/solids ratio was defined as the ratio between total mass of water (i.e. tap water + water in the alkali solutions) and the total solid mass (i.e. mass of pfa + mass of alkali solids). The water/solid ratio was kept in the range 0.35 – 0.37 as pfa-based geopolymers are very sensitive to water content.

Pfa-based systems require heat curing for the development of the reaction. The proposed curing regime was 7 days @ 70°C .

Development of a suitable mix design for façade panels and material characterisation

The following requirements were set by industrial partners for a mix suitable for façade panel production: slump in the range 9-20 cm, density of about 1100 kg/m³, compressive strength in the range 5-20 MPa. A mix design able to fulfil such requirements was developed and extensively investigated for its full characterisation. Mechanical (compressive strength, Young's modulus, Poisson's ratio, flexural strength, UPV) and thermal (thermal conductivity, thermal expansion coefficients, heat capacity, thermal storage capacity) properties were measured.

RESULTS AND DISCUSSION

Suitability of recycled aggregate in ordinary Portland cement concrete

Previous experimental activities demonstrated the feasibility of recycling mixed plastic scraps to obtain sustainable aggregates in the form of Remix HD and LD. The following step was the validation of their potential to be used for lightweight concretes. Therefore, their compatibility with traditional binder (ordinary Portland cement, PC) has been evaluated.

The specific target was to develop concrete formulations suitable for precast building components such as panels for façades (or part of them). During the trials the following requirements had been targeted for such concrete components: density 350-1700 kg/m³, workability S4-SCC and compressive strength 5-24 MPa. For this, different concrete mixes were designed and produced combining RX aggregates, natural aggregates and PC (type I 42.5 R, density 3.1 kg/m³). The formulations were optimized to get the target properties and their performance assessed both on the fresh (density, workability, air content) and hardened state (mechanical performance, thermal insulation properties, ultrasonic investigations), according to specific standards.

Different optimisation steps were implemented on the lab scale. Initially, compatibility evaluations of RX aggregates were carried out, i.e. preliminary concrete mixtures were produced and inspected whilst in the fresh state. The use of RX aggregates within concrete mixtures resulted in some undesirable effects, mainly swelling phenomena. This behaviour was related to a possible effect of residual impurities in the raw material used for aggregate production. In subsequent experiments cleaner aggregates were used and such problem was solved. The next step consisted in a systematic experimental programme, carried out in two different labs, for the identification of the best RX based concretes for the target application and for the assessment of their reproducibility. During the first experimental session several mix design parameters (i.e. water/cement, aggregates/paste and aggregates proportioning) were properly adjusted to obtain concretes with suitable density, consistency and mechanical performance. The best performing formulations produced during this phase are shown in Table 2.



Figure 2 Fresh (a) and hardened concrete samples (b, c) based on RX and OPC.

Table 2 Optimization of RX based concretes (1st step): design parameters and performance.

RX BASED CONCRETES (1 st OPTIMISATION TRIALS)								
Design parameters				Fresh performance		Hardened performance (28 days)		
Mix code	Cem [kg/m ³]	w/c	RX aggregate [% vol]	Density [kg/m ³]	Slump class	Density [kg/m ³]	Compressive strength [MPa]	Thermal conductivity @10°C [W/mK]
				EN 12350-6	EN 12350-2		EN 12390-3	EN 12664
Mix1	400	0.45	80%	1102	S4	1054	5.6	-
Mix2	400	0.45	70%	1172	S4	1120	5.9	0.25

Based on the results achieved, a further optimisation step was performed by a second lab. Using Mix 2 as reference, a more detailed study was carried out which monitored the effect of specific design parameters (i.e. RX aggregate percentage, water/cement ratio and cement content) on the final concrete performance. Therefore different RX aggregate volumes were incorporated (from 70% up to 100%), three different water/cement ratios (0.37, 0.40 and 0.45) and two different cement amounts (400 and 450 kg/m³) tested; one of the above mentioned parameters was changed in each trial. The results summarized in Table 3 are the most representative concretes produced during this experimental session.

Table 3 Optimization of RX based concretes (2nd step): design parameters and performance.

RX BASED CONCRETES (2 nd OPTIMISATION TRIALS)								
Design parameters				Fresh performance		Hardened performance (28 days)		
Mix code	Cem [kg/m ³]	w/c	RX aggregate [% vol]	Density [kg/m ³]	Slump class	Density [kg/m ³]	Compressive strength [MPa]	Thermal conductivity @10°C [W/mK]
				EN 12350-6	EN 12350-2		EN 12390-3	EN 12664
Mix3	400	0.45	70%	1102	S4	1063	5.5	-
Mix4	400	0.45	80%	910	S4	896	3.1	-
Mix5	400	0.45	90%	860	S4	819	3.1	-
Mix6	400	0.45	100%	734	S4	710	2.0	-
Mix7	450	0.40	70%	1191	S4	1183	8.9	-
Mix8	450	0.40	80%	1115	S4	1076	8.3	0.25
Mix9	450	0.40	90%	1108	S4	1097	9.0	-
Mix10	450	0.40	100%	908	S4	881	5.3	-

All the concretes based on RX aggregates showed a good reproducibility as well as a good compatibility with conventional mixing procedures. The density of all the concretes developed was suitable for the target application. The use of different percentage of RX aggregates did not affect the concrete workability (consistency class S4 in all the tests). As expected, higher plastic aggregate amounts resulted in lower compressive strength concretes.

Using 400 kg/m³ of cement and w/c 0.45 the compressive strength target is achieved only with 70% of RX, while incorporating more cement (450 kg/m³) and reducing w/c (0.40) all the formulations are suitable for panels fabrication.

Development of mix design with recycled aggregate and geopolymeric binder

The optimisation of the mix design was initially investigated varying the paste and the fine aggregate fraction proportions. The 0/2 mm RX aggregate was not used as it was found to cause heat formation, quick drying and swelling of the concrete, presumably due to the presence of residual impurities (such as metallic Al) in the aggregate. The fine fraction was therefore replaced with natural sand.

Paste proportion at 50% (mix RX1) was found to be too low for incorporating the aggregate, and therefore it was increased to 60%. Natural sand was dosed at 20% (mix RX2) and 30% (mix RX3) of the total aggregate volume. However, bleeding and segregation phenomena were observed. The flow was observed to be high and therefore a reduction in the w/s ratio was adopted for subsequent investigations.

Compressive strength was measured at 6 days for a quick assessment of its development. Mixes with 60% paste were found to satisfy the requirements (> 5 MPa), although concrete density was found to be slightly higher than the target value (i.e. 1100 kg/m³). Two further mixes (RX4 and RX5) similar to RX3 were cast with the aim of reducing the water content and therefore further increasing the strength, minimising possible bleeding and segregation phenomena. Mix RX4 was prepared with less paste (55%) with the aim of increasing the volume of aggregates incorporated. The sand content was kept equal to 30% of the total aggregate volume.

It was observed that, even with a water content reduction, the workability of the mixes was still compliant with the requirements. However, some bleeding was still observed during the execution of the spread test. The 28-day strength was confirmed to be satisfactory (> 5MPa). While workability and strength were in line with technical requirements, measured density was found to exceed the suggested value. However, it was judged satisfactory for façade panel production by industrial partners. Therefore, the mix RX4 was chosen for such application.

Table 4 Optimisation of RX + PFA concretes: design parameters and performance.

MIX DESIGN OPTIMISATION						
Mix no.	Paste prop. (%)	Sand (%)	RX 3/7 (%)	Slump (mm)	Hardened density (kg/m ³)	Compressive strength (MPa)
RX1	50	20	80	(collapse)	1413 ^a	3.6 ^a
RX2	60	20	80	210	1474 ^a	5.0 ^a
RX3	60	30	70	250	1605 ^a	5.8 ^a
RX4	55	30	70	170	1429 ^b	5.9 ^b
RX5	60	30	70	270	1432 ^b	5.6 ^b

^a measured at 6 days of age

^b measured at 28 days of age

Assessment of mechanical and thermal properties

Once the mix design was chosen, a comprehensive characterisation of mechanical and thermal properties of the SUS-CON concrete was carried out. Results from laboratory tests on RX4 mixes (carried out following relevant standards) are shown in Table 5. Fresh properties, compressive strength and hardened density were confirmed to be satisfactory and data were obtained for the thermal performance of the mix. Compressive strength, Young modulus and Poisson ratio were assessed by Magnetti Building (industrial project partner).

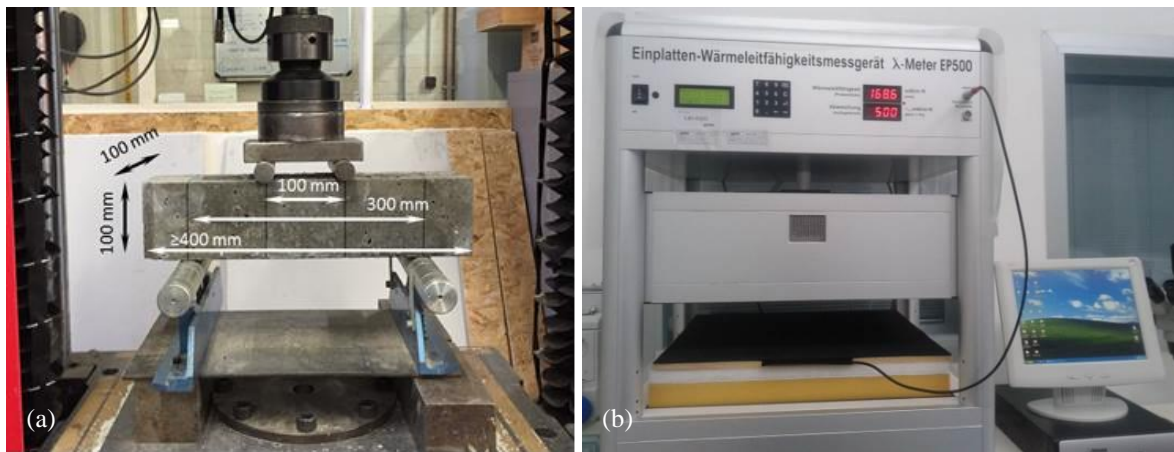


Figure 3 (a) Flexural test set up. (b) Hot plate apparatus for thermal conductivity evaluation.

MECHANICAL AND THERMAL FEATURES OF SELECTED RX MIX			
Parameter	Standard	u.o.m.	value
Slump	EN 12350-2	cm	23
Fresh density		kg/m ³	1636
Density (28 days)	EN 12350-6	kg/m ³	1440
Compressive strength (28 days)	EN 12390-3	MPa	6.8
Flex. strength (28 days)	EN 12390-5	MPa	1.3
UPV	EN 12504-4	m/s	1613.32
Young modulus	UNI 6556	GPa	1.0
Poisson ratio		-	0.05
Thermal conductivity (10°C)	EN 12664	W/mK	0.344
Heat capacity		J/g·°C	1.275
Thermal storage capacity		kWh/m ³	7.577
Coefficient of linear expansion (70°C)		°C ⁻¹	-3.36E-05

Panel production and mock-up structure and monitoring system

In order to demonstrate the feasibility of the SUS-CON products on full scale buildings and their real performance in terms of energy efficiency, 2 mock-ups were built with panel components (one with SUS-CON panels and a second one with Portland cement based-reference panel components). The mock-ups were constructed at ACCIONA Demo-Park (ACCIONA Central Workshop Facilities) in San Sebastián de los Reyes, Madrid.

Magnetti Building was in charge for the design and production of the prefabricated elements. A sandwich structure was chosen for the panel, with two external layers of SUS-CON concrete and an inner layer of EPS100. The panel design was defined for keeping the same weight and thermal transmittance of Portland cement based concrete panels typically produced in the facility. Panels were cast in Magnetti Building premises in Italy (see Figure 4) and shipped to Spain.

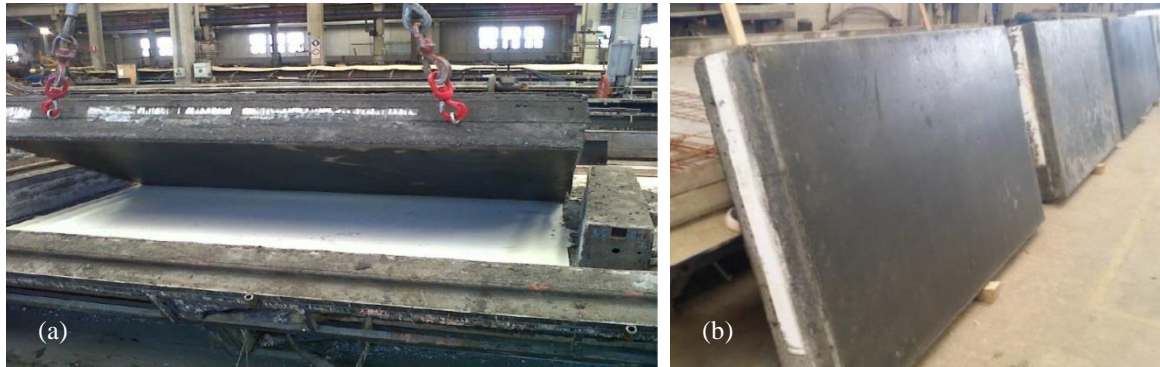


Figure 4 (a) SUS-CON panels demoulding, (b) cast panels (courtesy of Magnetti Building).

The dimensions of the mock-ups were 2.5 m each side, provided with a door and a window. The doors were located in the north wall and the windows in the east wall of the mock-ups. The internal walls of the mock-ups were coated with an insulating mortar and their external side was coated with a waterproof grey paint.

In order to monitor the thermal performance of the mock-ups, several probes were installed: two probes for indoor temperature (T1, T2), one temperature probe for indoor temperature on the walls (T3), one heat flux probe on the south wall (T5), one temperature probe for external temperature (T8) and one temperature probe for external temperature on the walls (T9). The windows were covered with a reflective aluminium layer in order to avoid direct irradiation on the probes and therefore overheating. The monitoring results presented in this paper correspond to the values recorded for 53 days (August/October 2015). Figure 5 shows the mock-ups during construction.



Figure 5 (a) SUS-CON panels mock-up, (b) reference panels mock-up, (c) two panels mock-ups finalized (front in the picture: SUS-CON; on the back: reference)

Mock-up temperature monitoring results

In order to analyse the energy efficiency of the built mock-ups, different charts of temperature versus time and different charts of heat flux versus time were obtained.

As far as the results on panel mock-ups are concerned, it can be observed that during the day the indoor temperature is 0.5 °C lower in the SUS-CON panels mock-up, and overnight the

indoor temperature inside the SUS-CON panels mock-up is 1.0-1.5 °C higher than the reference panels' mock-up. Both of these are considered positive from an energy efficiency point of view. Almost the same temperature oscillations between SUS-CON and reference panels mock-up were recorded. EPS layer in the panel may have had a relevant effect in the insulating properties, leading to quite similar results between SUS-CON and reference concrete. The heat flux in the SUS-CON panel mock-up resulted in slightly higher heat flux than the one obtained in the reference panel mock-up.

Figure 6 shows the trends of indoor temperature (T2) in the reference panels and SUS-CON panel mock-ups versus time.

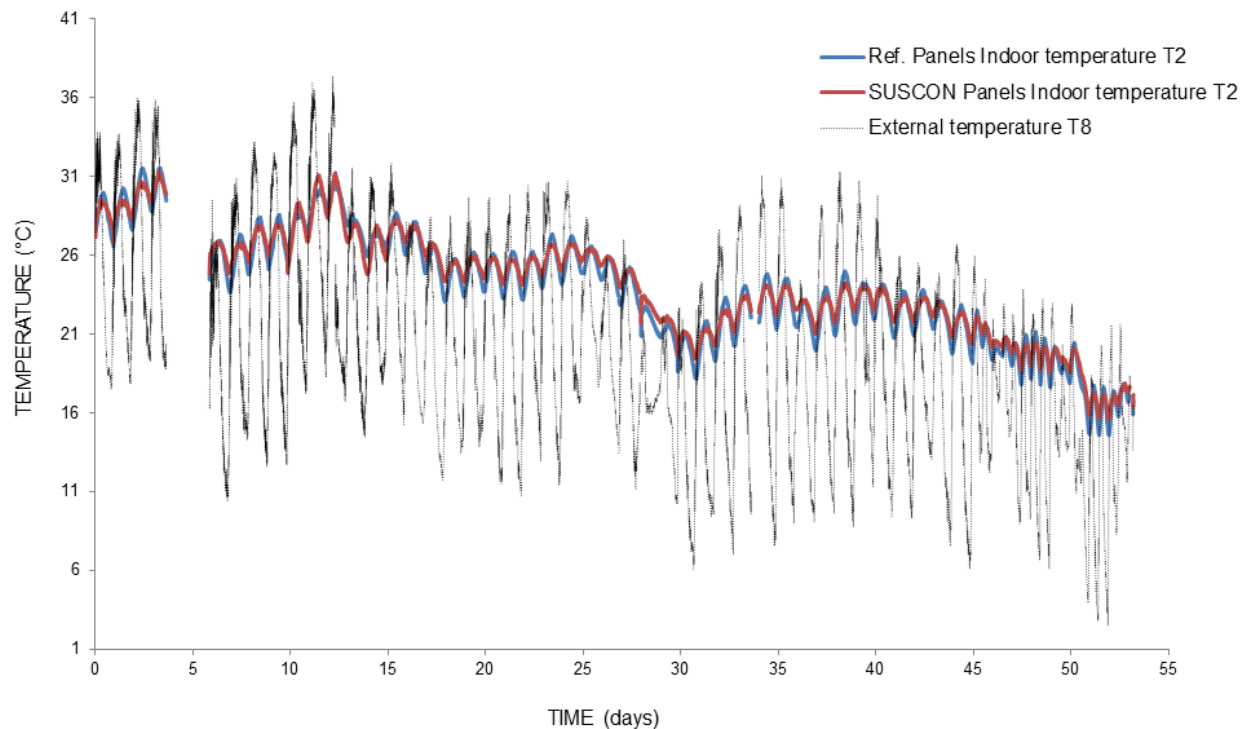


Figure 6 Temperature trends measured for at the demo site in Spain. The gap around day 5 was due to a loss of electricity.

The thermal inertia of the SUS-CON material was found to be lower than those of the reference construction material. This has obvious advantages from an energy efficiency point of view.

CONCLUSIONS

The SUS-CON project was funded under an FP7 call with the objective of developing new approaches to integrate secondary resource streams in the production of building materials, for both ready-mixed and pre-cast concrete. The project was successfully completed at the end of 2015, with the construction of mock-ups in three demonstration sites in Europe. Life Cycle Analysis and Life Cycle Costs analysis pointed out that the developed material fulfils the requirements of reduced carbon footprint, reduced embodied energy, and reduced cost. Practical applications of the developed materials are building blocks, façade panels and floor screed.

In this paper, some of the results obtained with a combination of aggregate from Mixed Plastic Waste and binder from fly ash were described. Aggregates were developed and their suitability in concrete was assessed through extensive testing with Portland cement. A pfa-

based alkali activated binder was developed and the compatibility of the two components (binder + aggregate) was assessed. A mix design fulfilling the technical requirements set by industrial project partners for the production of façade panels was developed, with a compressive strength of about 7 MPa, flexural strength of about 1.3 MPa and a thermal conductivity of 0.34 W/mK. Panels for the installation of a 2.5 m x 2.5 m x 2.5 m mock-up were designed and produced by Magnetti Building. SUS-CON mock-up and reference mock-up (made with Portland cement based concrete) were assembled in a demonstration park in Spain by ACCIONA and monitored over a time span of more than 50 days. Measurements of the internal and external temperature on site showed that SUS-CON material had good insulation properties, with lower thermal inertia than the reference construction materials. The industrial production of SUS-CON panels proved to be feasible with no major changes required from the current Portland cement based concrete production.

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